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Final Report

THEORETICAL ANALYSIS OF WAVE-PARTICLE
INTERACTIONS IN THE MAGNETOSPHERE
AND SOLAR WIND

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1. INTRODUCTION

The activities of the first three quarters were summarized in the quarterly reports dated 15 July 1972, 15 October, and 15 January 1973. In the final quarter, some new research programs were initiated. These studies are presently incomplete and it is anticipated that they will be completed under a new study program presently being discussed with Dr. L. D. Kavanagh, Jr. In the remainder of this final report, we discuss our progress in these new research activities.

2. THEORETICAL STUDIES

Theoretical Calculation of a Beam-Plasma Interaction

During the last few months of the contract, a calculation of the interaction of a phase-grouped particle beam (protons or electrons) flowing through a background plasma was begun. This calculation was motivated by a desire to study models of the backstreaming particles reflected at the bow shock.

Calculations have been carried out for beams described by the gyro-tropic but phase-anisotropic distributions

$$f_b(\underline{v}) = \exp \left[-v_{\perp}^2/a_{\perp}^2 - (v_{\parallel} - v_o)^2/a_{\parallel}^2 \right] \begin{cases} h(\phi - \omega_o t) \\ g(\phi - k_o z) \end{cases}$$

which is a drifting maxwellian distribution with a phase-grouping either modulated in time or in space along the background magnetic field (z-direction). The two functional forms of the phase coherent factors h and g used so far in our calculations are

$$h(\phi - \omega_o t) = \begin{cases} \delta(\phi - \omega_o t) \\ \exp(\phi - \omega_o t)^2 / (\Delta\phi)^2 \end{cases}$$

$$g(\phi - k_o z) = \begin{cases} \delta(\phi - k_o z) \\ \exp(\phi - k_o z)^2 / (\Delta\phi)^2 \end{cases}$$

where $\Delta\phi$ is an adjustable parameter measuring the spread in phase-coherence, i.e., $\Delta\phi \rightarrow \infty$ corresponds to random phase.

At the present time, dispersion relations for the full electromagnetic wave treatment of this problem have been obtained, but specific solutions for given plasma-beam parameters have not been completed in numerical form. These dispersion relations are sufficiently complex to require numerical analysis on a computer in the general case, and special cases in which justifiable approximations can be made that will lead to algebraically tractable dispersion equations are under investigation.

It is anticipated that these investigations will result in one or more published papers within a few months. Applications include the solar wind, near earth upstream wave generation observations, triggered or natural VLF emissions in the magnetosphere, as well as postulated uses of phase-coherent artificial beams to perform active magnetospheric experiments.

Theoretical Calculations on High Power Antenna-Plasma Coupling

Another set of theoretical calculations on the effects of impressing large ac voltages on a transmitting antenna immersed in a background (magnetized) plasma, such as that in the upper ionosphere, was initiated. By 'large' voltages, we mean peak antenna potentials $\phi_A \gg kT_e/e$, that is, antenna potentials large compared to the local plasma thermal potential.

The philosophy employed so far is to study the initial effects of the antenna electric field on the particle distribution function. For time intervals short compared to growth times of subsequent plasma instabilities, the first influence of such large impressed electric fields should be to reorganize the particle trajectories. Under certain conditions, for example those in which the antenna field can be approximated by a function of time only, say $E(t)$, the particle (orbit) equations of motion can be solved exactly. These perturbed orbits can then be fed back into the solution (by the method of characteristics) to Boltzmann's equation and the self-consistent Maxwell's field equations. One then obtains a 'linear' dispersion relation even for arbitrarily large antenna voltage. Since the new aggregation of perturbed particle orbits in the antenna field is equivalent to a large deviation from thermal equilibrium, it is unstable. Our calculations

should lead to a definition of the initial growth rates of a set of driven plasma modes [as well as a new set of 'normal' modes in the presence of $E(t)$]. For large input power levels from the antenna, these modes will rapidly be driven into a non-linear regime, where non-linear effects such as re-distribution of particles in phase space as well as parametric mode-mode couplings will ensue. These latter non-linear effects are not the subject of our present investigation.

The short-time-scale dispersion relations so far obtained are generally in the form of complex integral equations best solved by the already-developed electromagnetic and electrostatic Vlasov codes used at such institutions as Los Alamos and NRL, among others.

Another investigation carried out to the point of obtaining a dispersion relation, as well as some initial solutions indicating that instabilities are indeed possible under physically interesting plasma conditions, is that of generation of ion Bernstein modes and (perhaps lower hybrid resonance, as well) by an essentially dc electric field imposed on a magnetized cool plasma. This calculation has possible applications to the artificial generation of such modes by spacecraft fields, or in artificial controlled experiments. It will form the subject of a paper to be written in the near future.

3. ANALYSIS OF THE POLAR CUSP-MAGNETOSHEATH INTERFACE

The OGO-5 spacecraft penetration of the dayside polar cusp on November 1, 1968 presented scientists with a unique opportunity to study microscopic plasma physics phenomena along the low altitude cusp boundaries (IMP-5 had no wave instruments on board). Several basic papers on the measurements have already been completed, and the experimenters showed that plasma instabilities driven by field-aligned currents account for the high plasma turbulence levels observed. At low altitudes, wave-particle scattering seems to be strong enough to produce enhanced resistivity, so that the boundary field lines are not equipotentials.

We are now investigating another important aspect of these measurements at higher altitudes. Specifically, we find a strong shock-like discontinuity within the magnetosheath, upstream from the cusp-magnetosheath boundary. The work is presently incomplete, but a partial draft of a report on the phenomenon is contained in Appendix 1.

4. NEW TECHNOLOGY

In accordance with the requirements of the New Technology Clause (NASA Form 1162), no new inventions, discoveries, etc. were recorded or made for the duration of this contract.

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ROUGH DRAFT

APPENDIX I

PLASMA WAVES IN THE DAYSIDE POLAR CUSP.
PART 2: THE MAGNETOPAUSE AND POLAR MAGNETOSHEATH

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INTRODUCTION

In recent years space scientists have been able to confirm directly that the earth's magnetosphere is open. It is now known that some form of the solar wind plasma actually extends all the way to the ionosphere at high magnetic latitudes on the day side of the earth (Heikkila and Winningham, 1971; Frank, 1971; Russell et al., 1971). This dayside polar cusp or cleft connects to the auroral oval, and various wave-particle interaction processes that occur in the cusp region can affect the properties of the auroral particles, and contribute to scattering of particles into closed magnetospheric field lines. Recent studies of OGO-5 data, from a period on November 1, 1968 when the spacecraft entered the cusp during a large magnetic storm, showed that field-aligned currents drive certain plasma instabilities on the cusp boundaries at low altitudes (Scarf et al., 1972; Fredricks et al., 1973), and that Kelvin-Helmholtz or drift instabilities can produce other observed wave modes (D'Angelo, 1973; Fredricks, and Russell, 1973). The associated wave-particle scattering appears to be sufficiently strong to provide enhanced electrical resistivity so that parallel electric fields develop, and these parallel fields may account for some auroral acceleration phenomena.

Although the open versus closed magnetosphere configuration controversy is now resolved, and some understanding of the dynamical processes occurring in the low altitude cusp has been obtained, many fundamental questions concerning the structure and properties of the dayside cusp are still unanswered. One important area of uncertainty involves the phenomena that develop in the magnetosheath-polar cusp interface region. It was recognized long ago (see, for instance, Dungey, 1958) that the conventional conditions used to define the local

orientation of the magnetopause give singular results at the neutral points, and this fact requires the existence of an indentation in the boundary near each neutral point. Walters (1966) noted that the boundary indentation occurs in a region of supersonic magnetosheath flow, and he suggested that this would result in the formation of a neutral point shock wave attached to the magnetopause. However, Spreiter and Summers (1967) argued that attached shocks of this type would not develop because the magnetosphere is not a solid obstacle to the flow. These authors developed a very different model for fluid flow around the high latitude magnetosphere, by allowing the obstacle to adjust its boundary shape. They introduced the concept of a smooth streamline of constant pressure across the neutral point indentation to separate the supersonic magnetosheath flow from a hot stationary or stagnant plasma trapped in the cusp-shaped region in the vicinity of the indentation.

The discussions of Walters (1966) and Spreiter and Summers (1967) were both based on conventional fluid flow treatments, and in each case tacit assumptions were made concerning the significance of collective plasma physics effects. For the attached shock to form in the collisionless magnetosheath plasma some kind of plasma instability, perhaps similar to that observed in the bow shock region (Fredricks et al., 1970), would be required to provide the necessary dissipation mechanism. It is less certain that wave-particle interaction effects significantly modify the Spreiter-Summers predictions, but several points may be noted: a) conclusions about the general shape of the magnetopause near the neutral points follow from use of conditions that the divergence and curl of the magnetic field vanish. If wave-particle interactions provide sufficient enhanced plasma resistivity, then currents can flow, and the curl of \mathbf{B}

may not be negligible; b) the hypothetical streamline separating the stationary trapped plasma from the supersonic magnetosheath flow represents an extreme discontinuity in the plasma distribution functions. If particles diffuse across this boundary or if turbulence in the flow causes the local boundary position to oscillate, then stationary plasma particles could be injected directly into the supersonic magnetosheath plasma flow. These considerations suggest that this fluid streamline may actually represent the average position of a highly unstable form of discontinuity.

On November 1, 1968 the OGO-5 spacecraft penetrated the dayside cusp at low altitudes, and it also traversed the magnetosheath-polar cusp interface region. In this report we discuss the OGO-5 plasma wave and magnetic field observations in the expected region of the neutral point. The magnetopause is tentatively defined in terms of changes in the low frequency magnetic fluctuation levels, and it is shown that a strong discontinuity, marked by a distinct enhancement and variation in the high frequency plasma turbulence spectrum, was encountered beyond this magnetopause. The analysis of the OGO-5 field and wave measurements is supplemented by comparison with simultaneous interplanetary magnetic field orientation data from Explorer 33, and the results are discussed in terms of the Walters and Spreiter-Summers predictions. If we assume that the November 1, 1968 observations are typical of neutral point phenomenon, rather than being associated with the large magnetic storm, it can be concluded that collective plasma physics processes do play an important role in this region of the magnetosheath.

GENERAL DESCRIPTION OF THE OGO-5 MEASUREMENTS

On November 1, 1968 the OGO-5 satellite was outbound through the dayside magnetosphere, and the trajectory remained close to the 45° magnetic latitude projection out to about 10-11 earth radii. At 1220 UT, when the spacecraft altitude was $2.2 R_e$, the solar wind plasma probe first detected large fluxes of warm electrons with characteristic magnetosheath energies ($N_e \approx 10 \text{ cm}^{-3}$, $kT_e \approx 200 \text{ eV}$), and Russell et al., (1971) interpreted these observations in terms of the initial OGO-5 encounter with the dayside polar cusp plasma. There were several additional isolated cusp encounters between 1250 UT and 1330 UT, and after about 1345 UT (spacecraft altitude equal to $6 R_e$), electrons with $kT_e \gtrsim 300 \text{ eV}$ were continuously detected. The central panel in Figure 1 summarizes these electron measurements in terms of an energy density versus time plot. The top and bottom panels of this figure contain general information on the changes in VLF electric field wave amplitudes (for each 3.23-minute interval, the maximum and minimum values of the wideband 1-22 kHz levels are plotted), and the ULF magnetic fluctuation variations (B_{RMS} is the standard deviation for a one-minute accumulation of magnetometer data).

Several very detailed studies of the low altitude cusp properties on November 1, 1968 have already been completed. Scarf et al. (1972) presented a general survey of the ULF and VLF activity out to 1500 UT ($r \approx 9 R_e$), along with an intensive analysis of the cusp boundary observations before 1345 UT. Fredricks et al. (1973) and Fredricks and Russell (1973) carried out more detailed studies of these low altitude measurements, and the authors showed that for $r \leq 6 R_e$ the most intense wave activity developed in small subregions where strong field-aligned currents flowed. Kivelson et al. (1973) analyzed

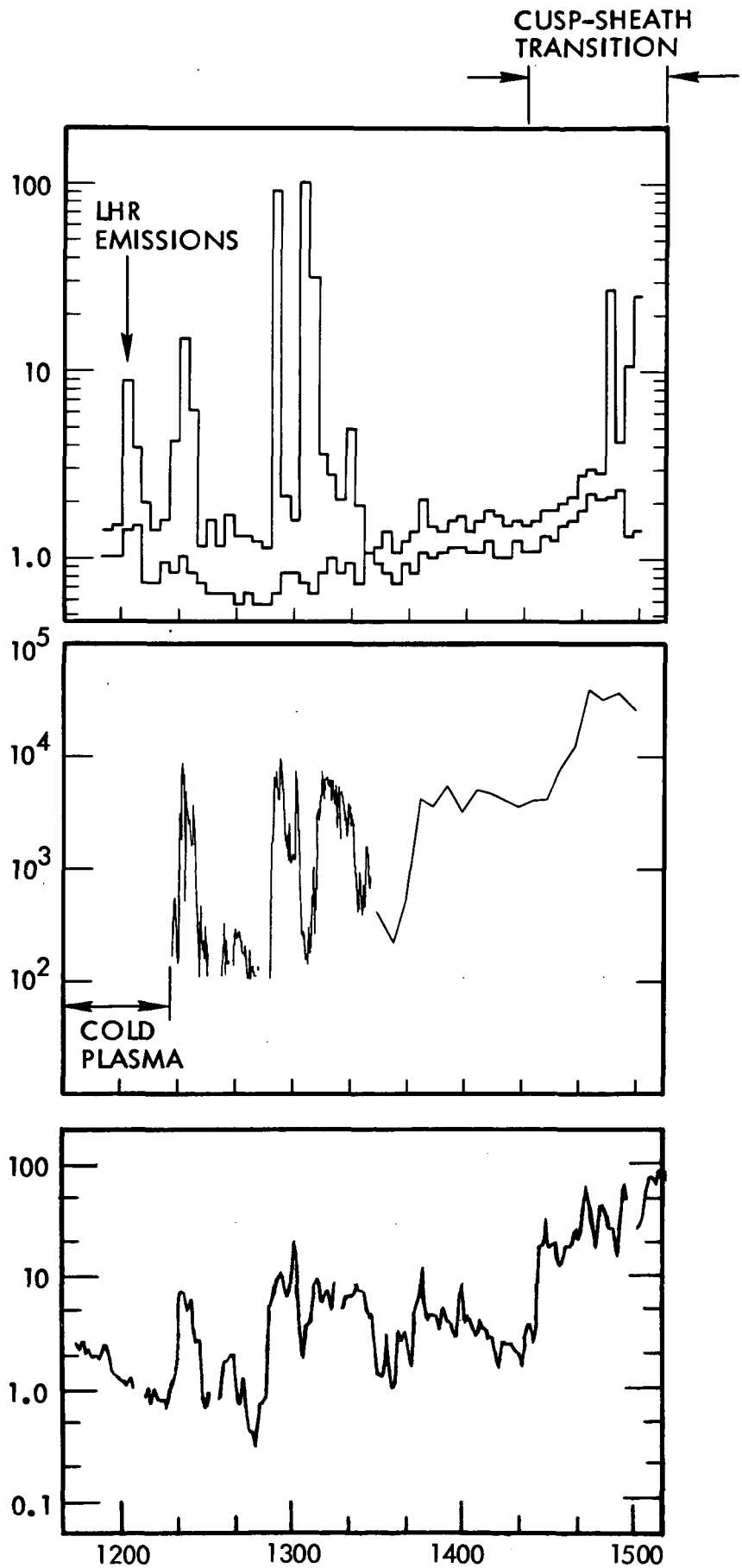
the motion and changes in structure of the cusp in terms of response to variations in interplanetary or magnetosheath field orientation; a brief discussion of the phenomena observed in the interval between 1345 and 1430 UT does appear in the report by Kivelson et al., but once again the emphasis in the study was on the measurements made before 1345 UT, when OGO-5 was well below the magnetosheath.

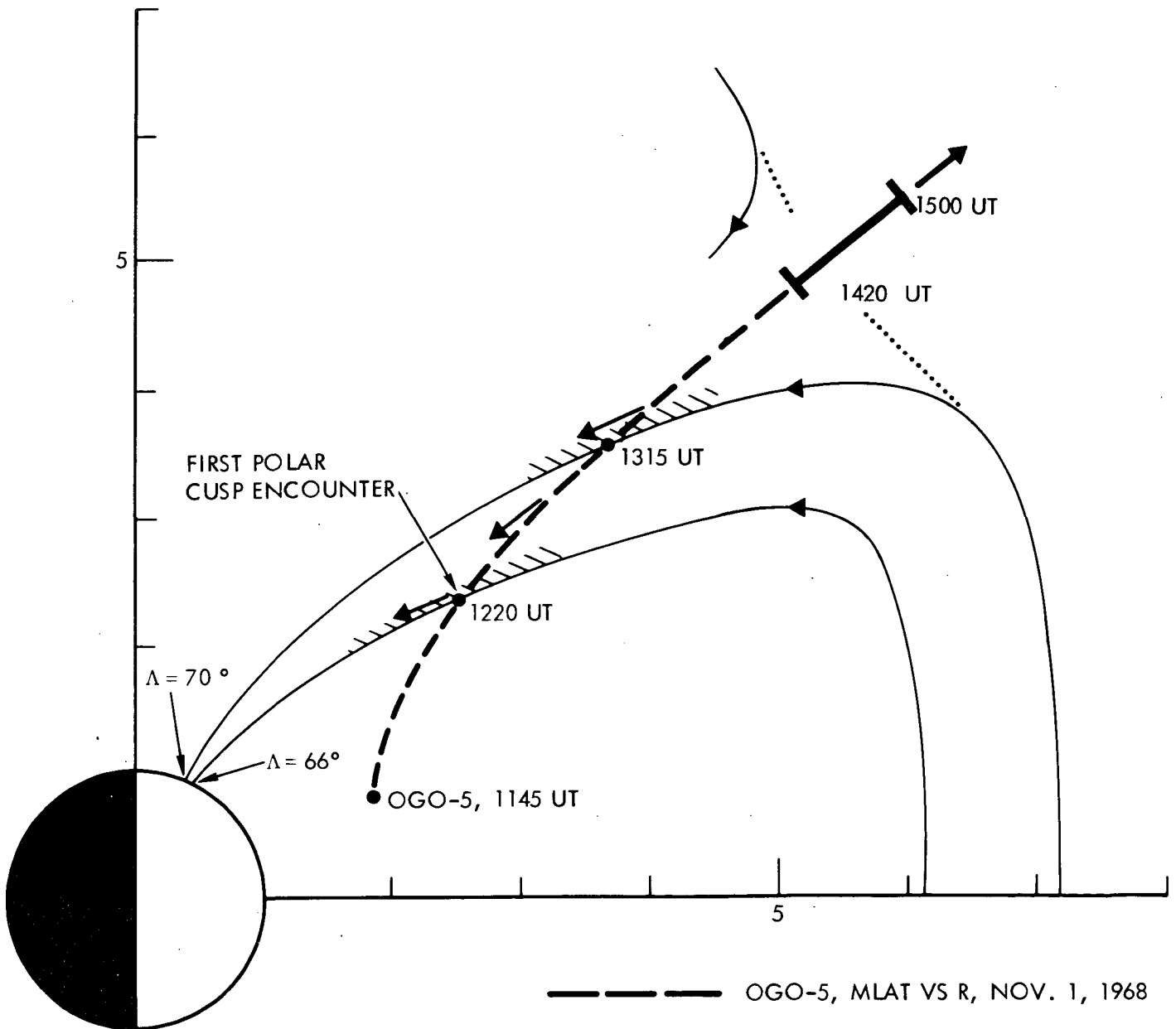
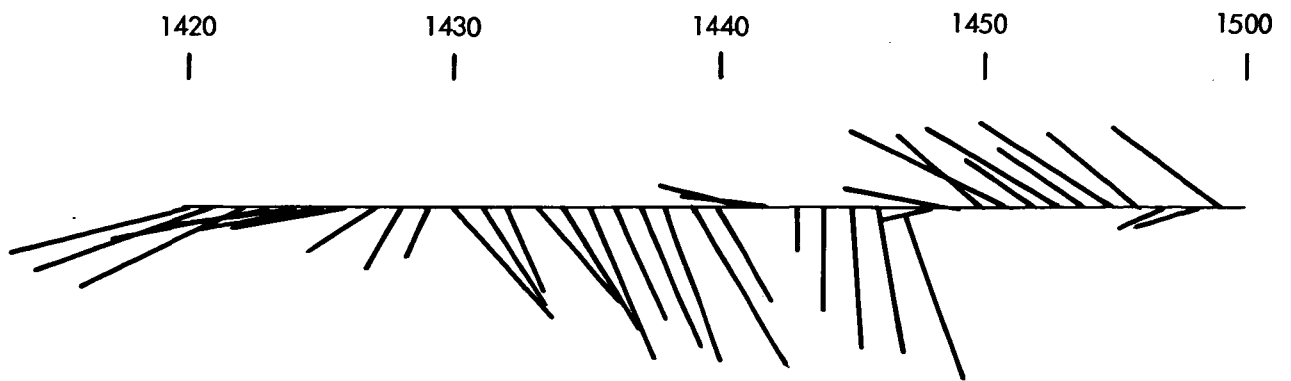
In the remainder of this report we focus attention on the OGO-5 measurements made after 1420 UT, when the spacecraft was emerging from the dayside polar cusp into the magnetosheath proper. The lower part of Figure 2 shows the OGO-5 trajectory (radius versus magnetic latitude) for the interval 1145-1500 UT on November 1, 1968, and the spacecraft location for the period of special interest (1420-1500 UT) is marked by a heavy line segment. The light curve marked "first polar cusp encounter" and the corresponding one that intersects the trajectory at 1515 UT are taken from Figure 13 of Russell et al. (1971). The short arrows show the measured magnetic field orientations in these coordinates between 1220 and 1315 UT, and the cusp boundary curves are drawn by requiring the field to be parallel to the observed field near OGO-5, and dipolar near the earth. Above the OGO-5 trajectory curve we sketch a possible form for the polar cap boundary of the cusp, to show the general field orientation expected in this region.

WIDEBAND (1-22) KHz
ELECTRIC FIELD LEVELS,
MILLIVOLTS/METER

ELECTRON
ENERGY
DENSITY,
 $\text{EV}/(\text{CM})^3$

B_{RMS}
GAMMA

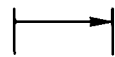




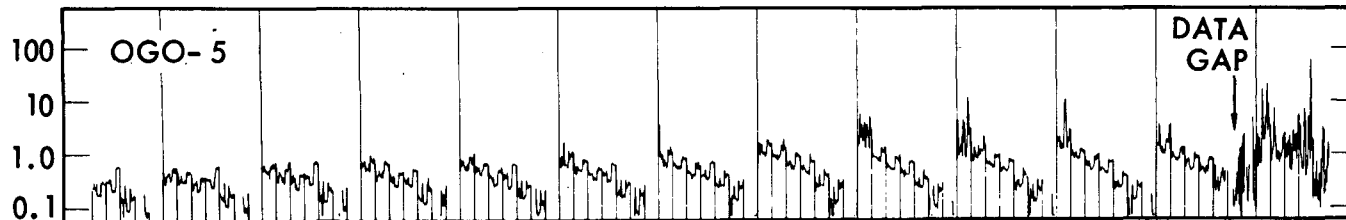
13 Figure 2

NOV 1, 1968

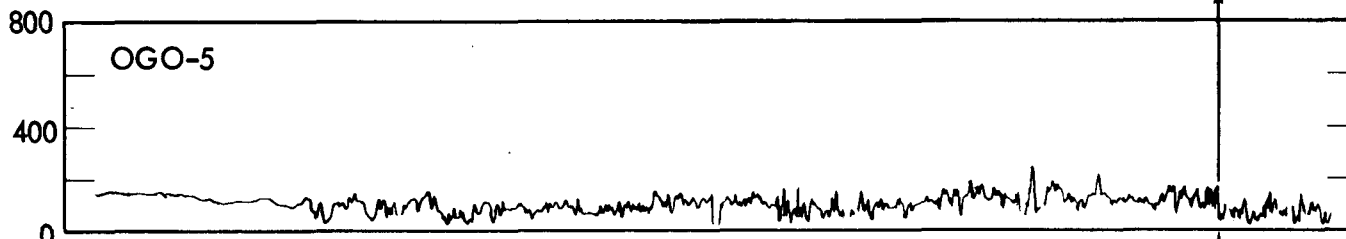
0.56 TO 70 KHz SCAN



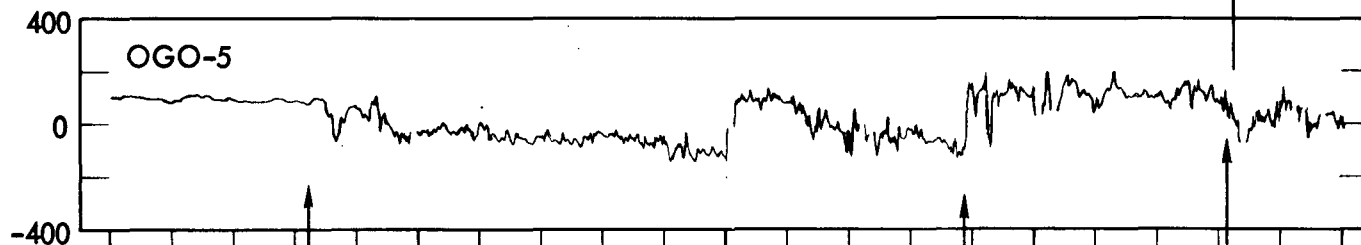
E,
MILLIVOLTS/METER



$|B|$,
GAMMA



B_1 -COMPONENT,
GAMMA



1420 1430 1440 1450 UT 1500

POLAR CUSP

HIGH LATITUDE
MAGNETOSHEATH

(B_Z) GSM,
GAMMA

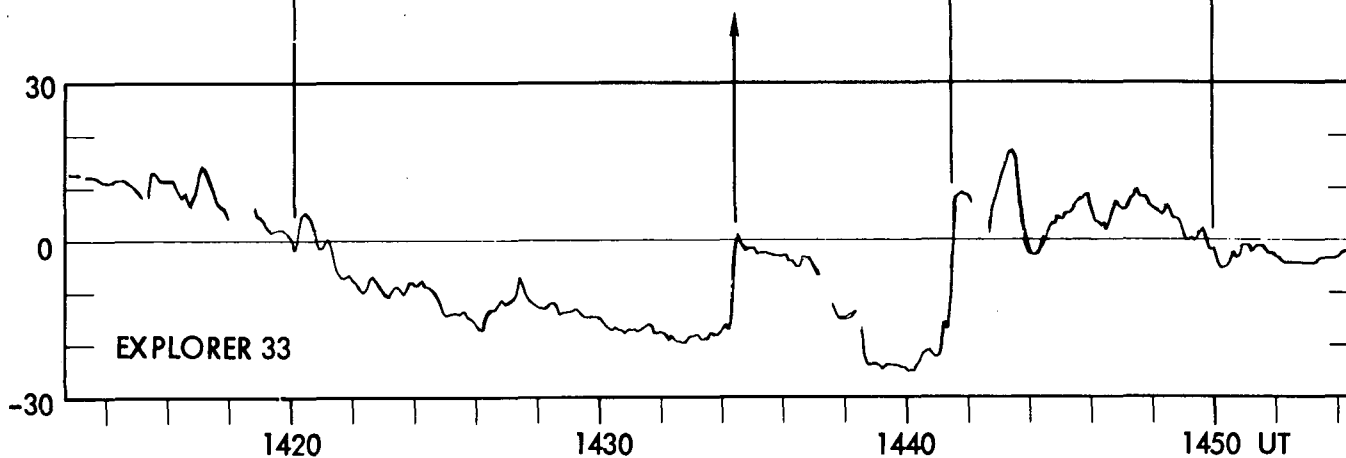


Figure 3

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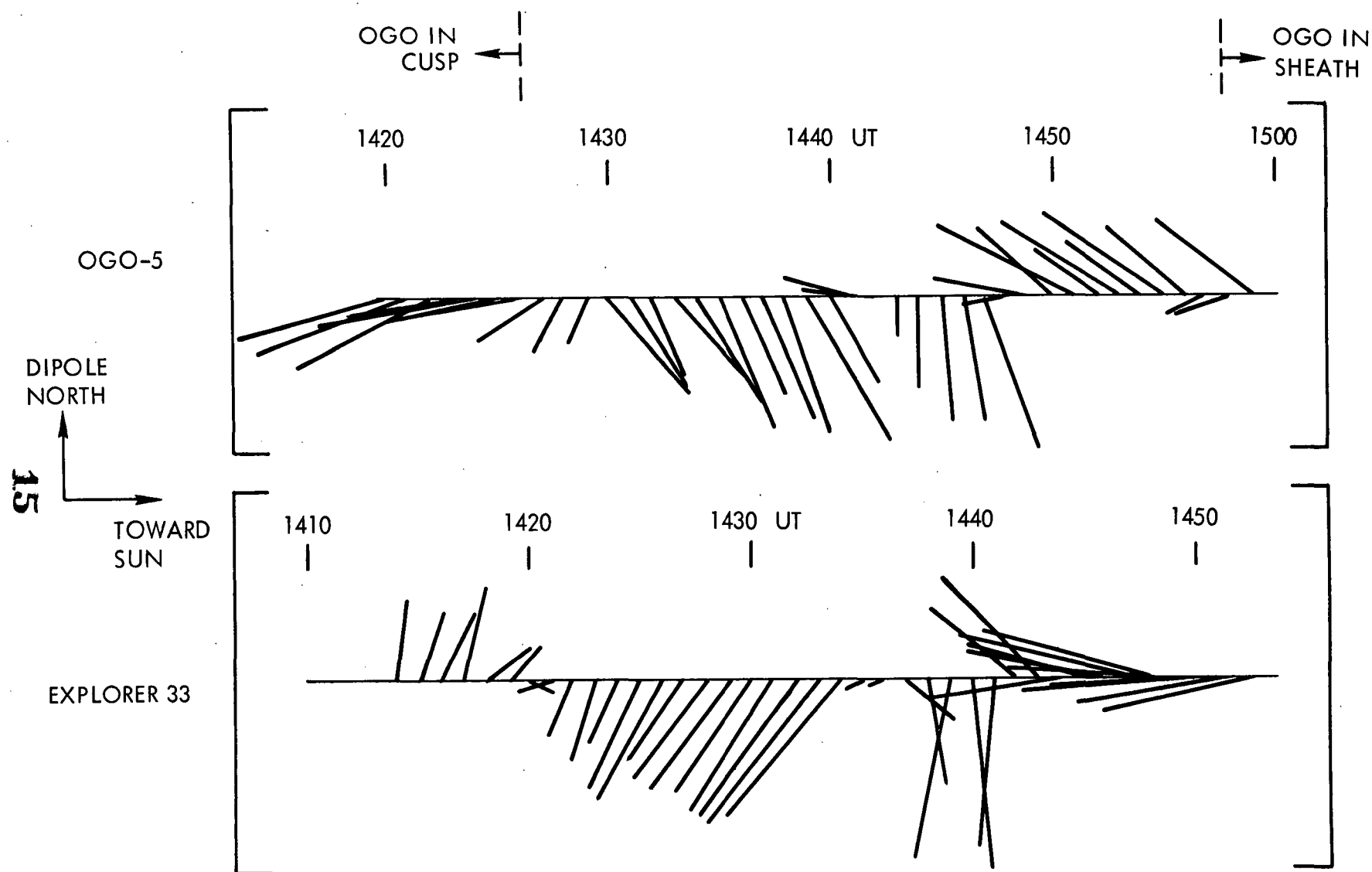
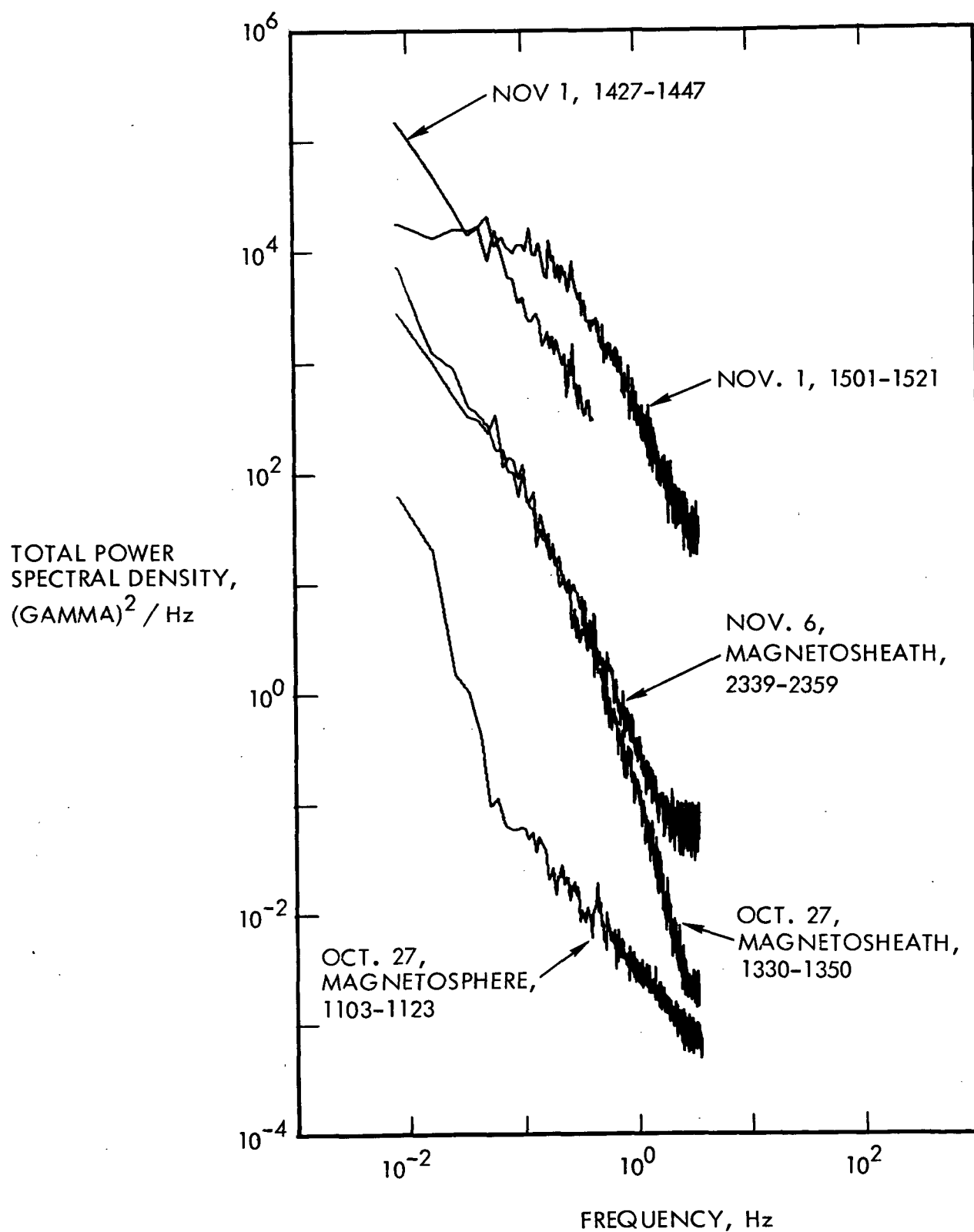


Figure 4



OGO-5 NOV. 1, 1968

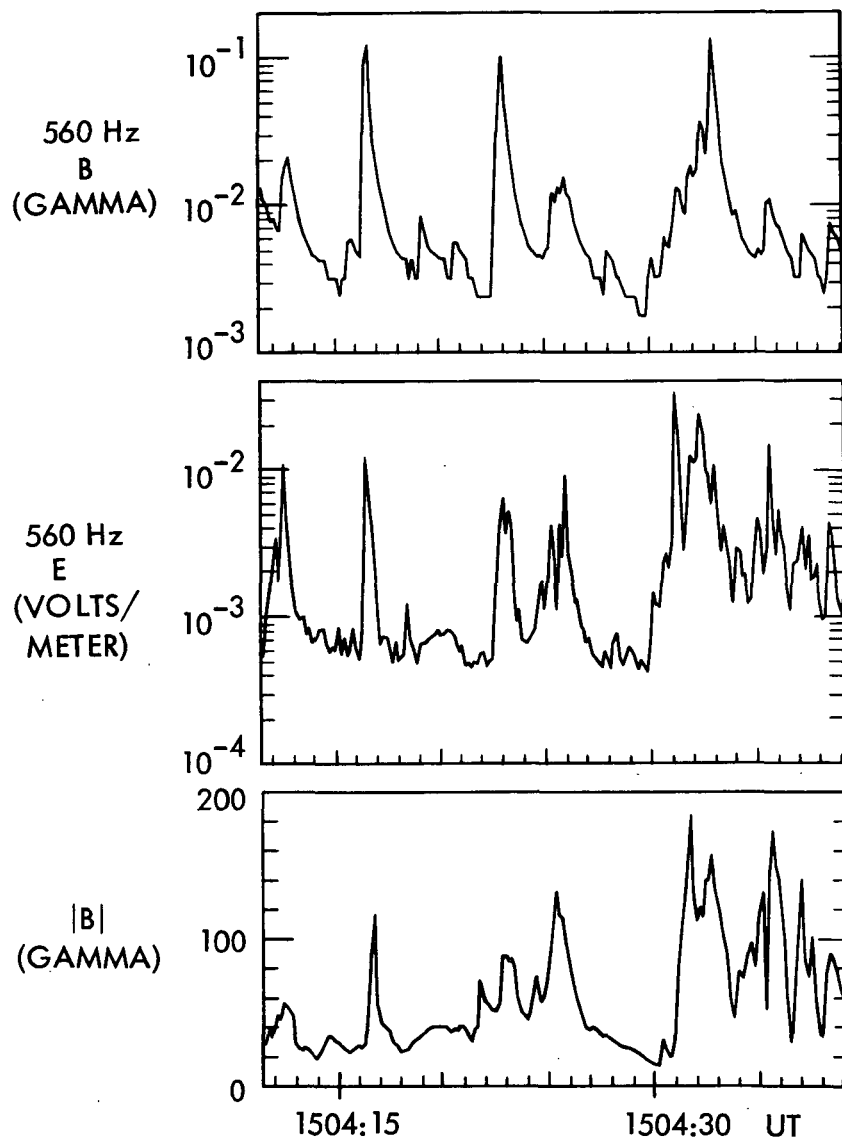


Figure 6

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OGO-5, NOV. 1, 1968

$r = 8.2 R_e$, MLAT = 42.7° , LT = 1437

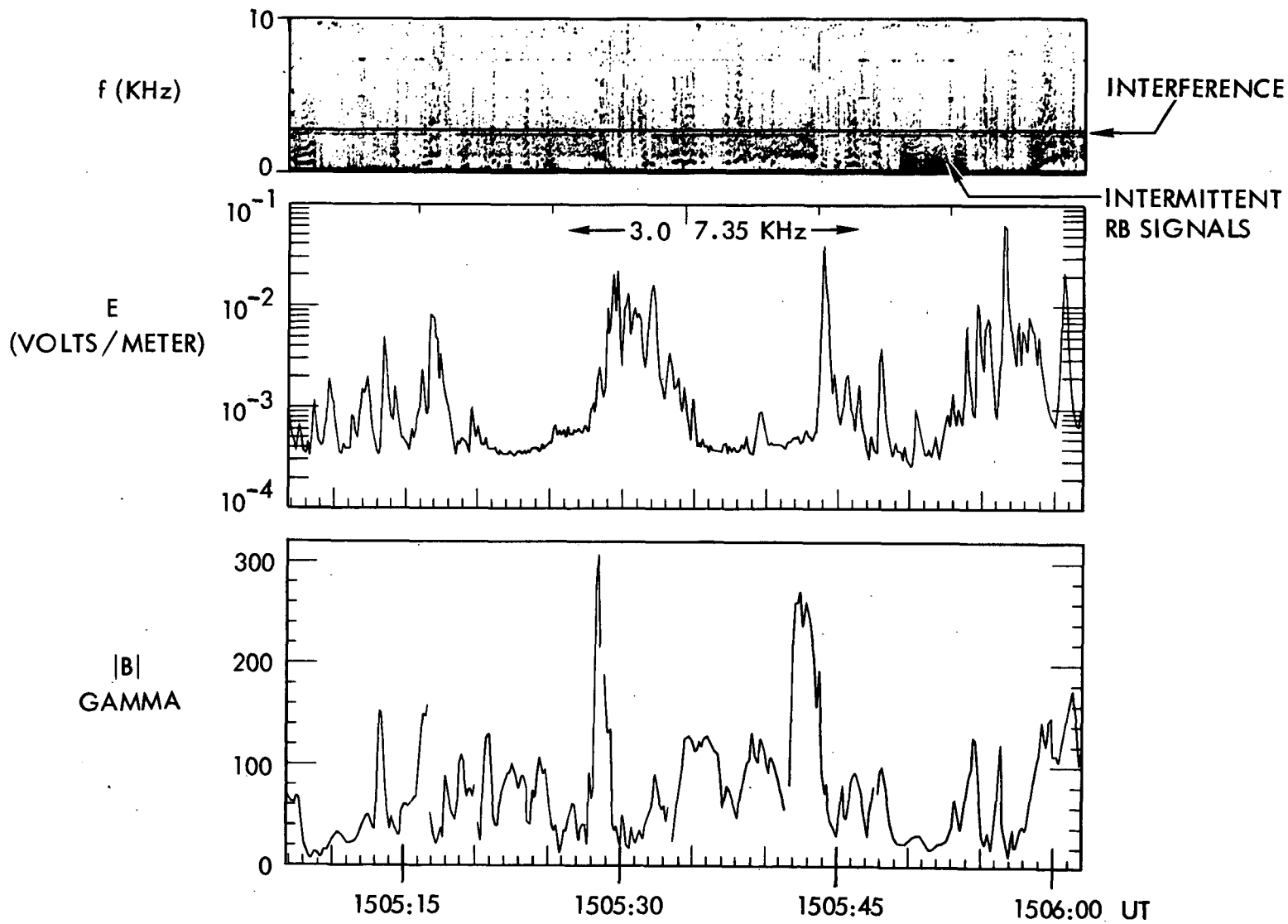


Figure 7

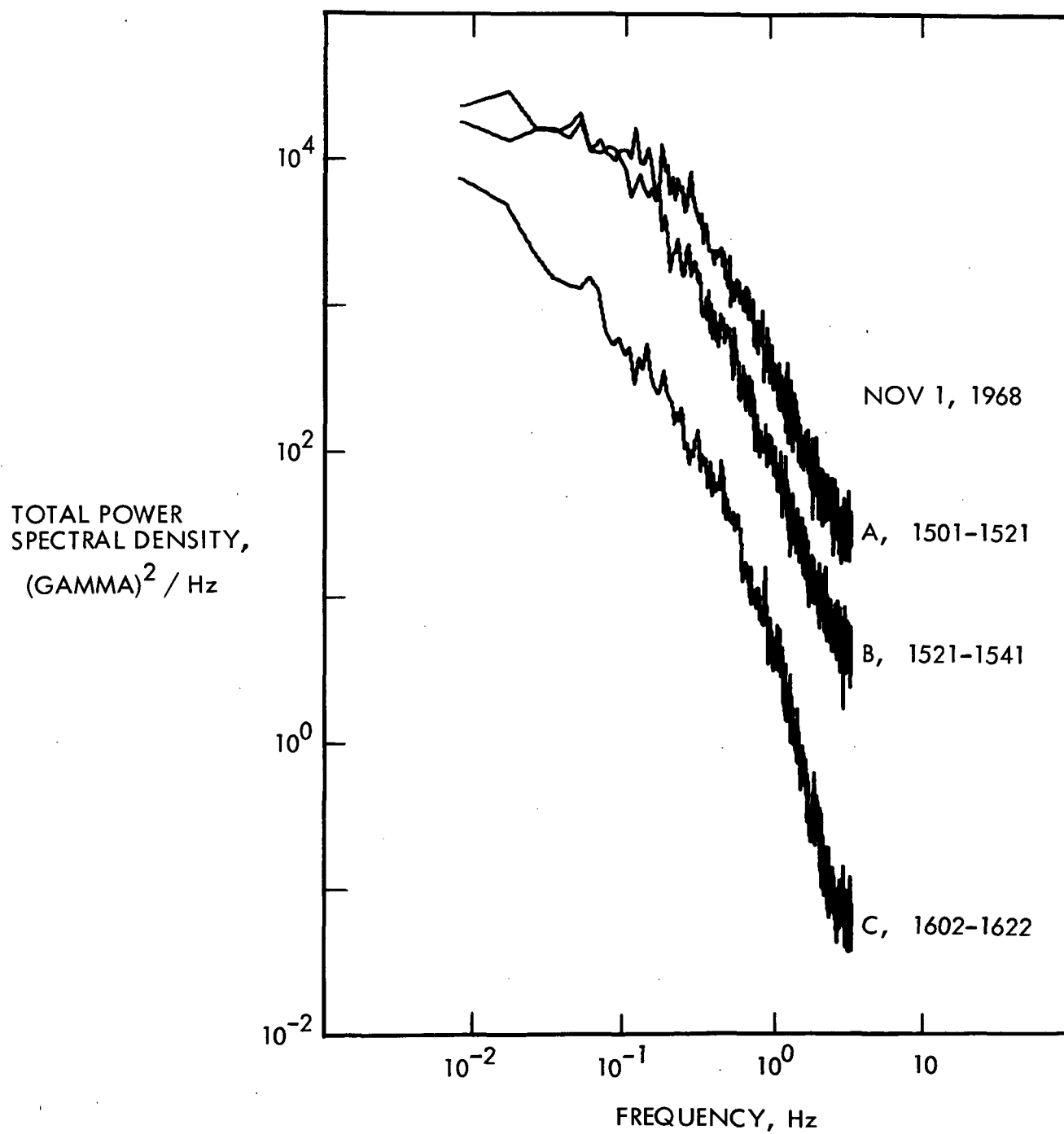


Figure 8